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SYNOPSIS San Francisco's Southwest Ocean Outfall will extend four miles into the Pacific Ocean. Offshore, the Outfall will cross the San Andreas fault zone. Major design concerns for the 12-foot inside diameter reinforced concrete pipe included seismic foundation stability, backfill liquefaction, and rupture by fault displacement. Foundation stability was achieved by selection of adequate embedment depths. A coarse pervious backfill to preclude liquefaction-induced porewater pressure gradients was selected based on analyses with the computer program APOLLO. Special joints were designed within and adjacent to the fault zone to limit damage due to fault rupture and to accommodate deformations away from the major fault slip.

INTRODUCTION

The Clean Water Program of the City and County of San Francisco will provide improved collection, transportation, treatment, and disposal of sanitary and storm wastewater flows. After passing through a system of transport lines, treatment plants, and tunnels, these flows will reach the proposed Southwest Ocean Outfall,where they will be dispersed at a diffuser section located in the Pacific Ocean approximately four miles southwest of Lake Merced as shown on Figure 1.

Since 1977, the project design team has conducted various data acquisition and analysis programs (Belvedere et al, 1978; Treadwell et al, 1978; Murphy et al, 1979; Treadwell et al, 1980). The results of these studies have been incorporated in the planning, preliminary design, and final design efforts which were completed in late 1980.

The proposed Outfall will be a single conduit composed of reinforced concrete pipe sections with an inside diameter of 12 feet extending about 22,000 feet offshore. The water depth at the Outfall terminus is about 80 feet. Throughout its length, the Outfall will be embedded in a trench excavated as much as 25 feet below the existing seafloor. The design gravity flow rate of the Outfall system is 450 million gallons per day.

About 8700 feet offshore, the Outfall will cross the San Andreas fault zone, one of the world's major active faults. Thus, ground shaking and fault displacement were among the major design concerns of the project. In this paper, the geotechnical investigations are reviewed and geotechnical conditions pertinent to seismic design are presented along with discussions of specific Outfall design features meant to resist or accommodate earthquake forces and fault displacements.

GEOTECHNICAL INVESTIGATIONS

The offshore geotechnical investigations for the project included:

- surf zone borings using a truck-mounted rotary drill rig on a self-propelled shallow-water work platform
- offshore borings, vibratory corings, and cone penetrometer tests using a specially-equipped and modified drillship
- marine geophysical surveys using an ocean survey vessel equipped with precision electronic navigation and fathometer systems as well as specialized seismic reflection, sonar, and magnetometer systems
- test pit construction and monitoring using a derrick barge clamshell dredge and an ocean survey vessel

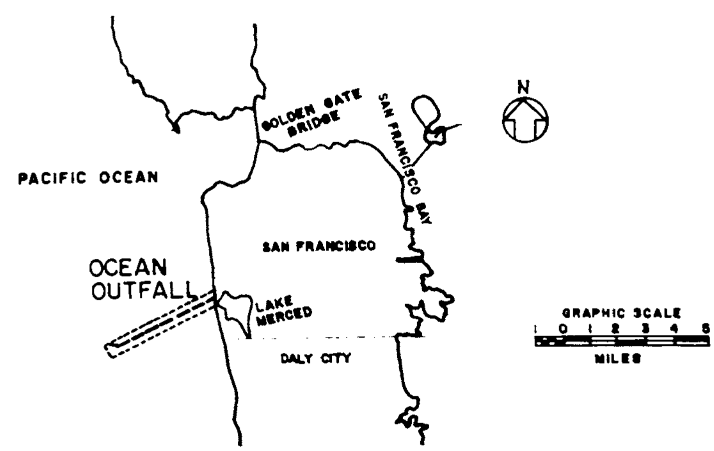

Figure 1 VICINITY MAP OF PROPOSED OUTFALL

Three sampled borings were completed in the surf zone to an average depth of about 200 feet below the seafloor. The borings provided geotechnical information for the design of a tunnel under the surf zone as well as for the cut-and-cover construction approach. The surf zone tunnel remains as a contract bid alternate.

Offshore, the drillship program provided ten sampled borings with an average depth of about 60 feet, sixteen vibratory corings with an average depth of about 12 feet, and sixteen cone penetrometer tests ranging from 4 to 20 feet into the seafloor. The drillship program was planned to provide a variety of geotechnical information within the depth of interest over a fairly wide area.

The marine geophysical and bathymetric surveys included a general survey covering an area in excess of 40 square miles and a site-specific survey concentrated primarily on the Outfall alignment. Over 400 nautical miles of geophysical data were collected, resulting in more than 4000 feet of analog records. For project purposes, the data were reduced, mapped, and correlated with the results of other geotechnical exploration programs.

The offshore test pit program included eight weeks of dredging and a monitoring period extending more than 24 months. Two test pits were excavated by a derrick barge clamshell dredge to depths of approximately 25 feet below the seafloor. Information was obtained concerning dredging rates, spoils disposal techniques, and the short-term and long-term behavior of the pits, including observations of slope stability and rates of infilling.

GEOTECHNICAL CONDITIONS

Soils

The offshore soils along the alignment are predominately dense to very dense fine sands. Within the surf zone, extending to about 4500 feet offshore, the ocean bottom consists of a generally loosely consolidated layer of sand 2 to 8 feet thick, underlain by hard clayey silts and silty clays. These cohesive soils are underlain by dense to very dense sands with occasional lenses of fine gravel.

From about 11,000 feet offshore and westward, the surface sands are underlain by medium stiff to stiff, moderately overconsolidated silty clays which grade to clayey and sandy silts at greater depths. The top of the clays appears to vary from 15 to 35 feet below the seafloor, based on the boring and geophysical data. The relatively level top of the cohesive soils apparently represents an ancient, buried shoreline.

A thin veneer of loose surface sands was encountered along the entire alignment. This layer is typically 2 to 4 feet thick, but in localized areas is as much as 6 to 8 feet thick. Beneath the surface veneer of loose sands, the sands increase in density with depth, from medium dense to very dense.

Faults

Offshore fault zones located in the project vicinity are the San Andreas, Pilarcitos, and Seal Cove (see Figure 2). The latter two faults were found to be westward of the Outfall, so efforts were focused on defining the width and orientation of the San Andreas fault zone at the Outfall alignment.

Between the surf zone and the San Andreas fault, there is a series of tightly-folded, thin-bedded sediments. These sediments may be correlative with similar outcrops seen on the shore. The limbs of the folds dip approximately 10 to 20 degrees. The fold axes plunge to the northwest, and the width of the geological structures decreases toward the fault.

In the vicinity of the Outfall alignment, the location of the San Andreas fault trace is represented by a blurred zone which does not show internal structure across the zone. This zone marks a transition between tightly-folded sediments to the east and relatively horizontally-bedded sediments to the west.

Along the outfall centerline, the San Andreas fault zone was determined to be approximately 400 feet wide. The strike of the fault zone is approximately N39°W, which is 12 degrees west of perpendicular to the Outfall alignment.

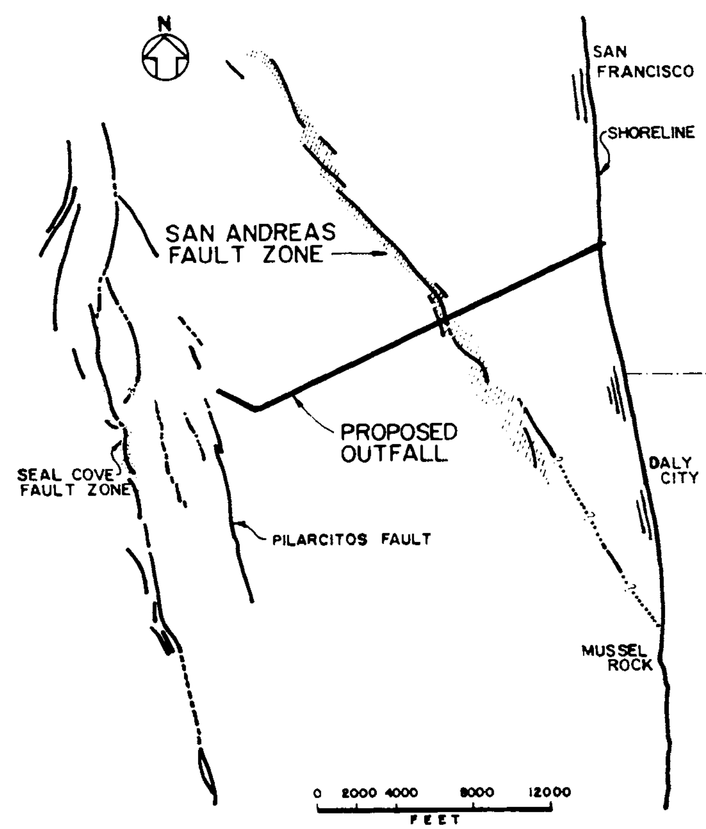

Figure 2 OFFSHORE FAULTING IN PROJECT AREA

DESIGN OF THE OUTFALL SYSTEM

The design of the Outfall system is based on resisting or accommodating the various forces or deformations it is likely to encounter during its 75-year design life. Of prime concern are the effects of seismic activity in the project area and the potential hazards of crossing the San Andreas fault zone. On occasion, however, the potential effects of waves and currents overshadowed seismic concerns.

Of particular design interest are the offshore Outfall conduit and diffuser sections, special joints at and near the fault zone, the excavation depth of the Outfall trench, and the gradation and geometry of the backfill that will be placed around the conduit. These elements of the system, along with the seismic design parameters utilized, are discussed in the following sections.

Seismic Design Parameters

Based on a review of historical seismicity, a design earthquake of Richter magnitude 8+ has been selected for the project, with a peak ground acceleration of 0.6g, a transient displacement of 20 inches, and a peak velocity of 30 inches per second.

The potential magnitude and distribution of fault displacements during the design earthquake was based on a review of 38 case histories of linear structures offset by the San Andreas fault during the 1906 earthquake. It was concluded that the Outfall could be subjected to relative (right-lateral) horizontal displacements of 16 to 20 feet, with relative vertical displacements of 3 to 4 feet.

While the case histories indicated that a major portion of the relative displacement occurred within a narrow zone along the fault trace, the remaining offset was often distributed over a relatively broad deformation zone extending beyond the fault (see Figure 3). The potential for significant deformations away from the fault trace was a major consideration in the design of the pipe joints.

A review of geodetic measurements suggests that about 6 inches of relative fault creep displacement can be anticipated during the 75-year life of the Outfall.

Outfall Conduits and Diffusers

The following forces and potential movements proved to be major factors in the design of the offshore Outfall system:

- potential fault displacements during the design earthquake (see Figure 3) and shear forces due to long-term creep
- stresses and strains caused by shaking, twisting, elongation, and shortening associated with seismic waves propagating through the soil surrounding the conduit. A response to this concern was the selection of bell-and-spigot joints including a one-foot-long spigot with two "O"-ring gaskets and a bending angle capacity at the joint exceeding 2 degrees
- forces caused by fishing nets dragged along the seafloor by trawlers which may snag on the diffuser caps. Surprisingly, these lateral forces on the diffuser risers proved to be far greater than the seismic or wave forces and thus became the design load
- wave-induced surge pressures in the conduit caused by series of large waves during major storms. Additional spiral reinforcement was required for the conduit and larger bolts were added to the manhole hatch covers to resist these potential surge pressures

Special Joints

Special joints were designed for a 1200-foot section of conduit centered on the 400-foot-wide San Andreas fault zone. Their main feature is a sliding joint consisting of a 5-foot-long steel pipe sleeve with special gaskets, keeper plates, and stopper plates.

The sliding joints permit segmental bending in excess of 4 degrees, elongation of about 30 inches and longitudinal shortening of about 12 inches. The sliding joints will be placed every 50 feet along the special joint section.

Locking joints secure each side of the sliding joint sleeve assembly to the adjacent concrete pipe segments. Locking joints are also placed at the bell-and-spigot joints between the concrete pipe segments that are placed between the sliding joints.

When the capacity of a sliding joint to either elongate or to shorten is reached, the locking devices transmit the load and engage the next sliding joint 50 feet away. This process can be repeated again until the last sliding joint reaches its capacity. Figure 4 is a longitudinal section showing the arrangement of the sliding and locking joints.

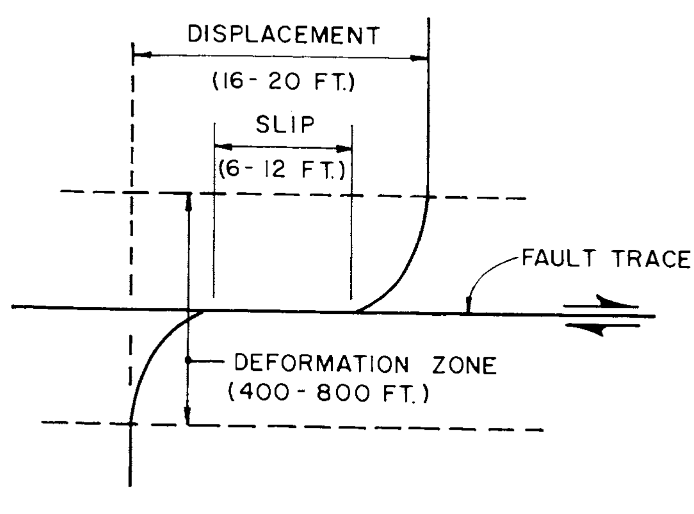

Figure 3 POTENTIAL FAULT DEFORMATION

In summary, the special San Andreas fault zone joints are designed to withstand all loads that may be anticipated during the life span of the Outfall with one exception. Should a 20-foot slip occur along the San Andreas fault, the Outfall conduit will almost certainly break. In this case, provisions were made to excavate and expose two or more manholes on the shoreward side of the break, remove their covers and replace them with specially designed emergency diffuser units. These units will diffuse the effluent about 1.5 miles offshore during the repair operations.

Trench Excavation Depth

The major factors in establishing the minimum trench excavation depths for the embedded Outfall conduit were seismic foundation stability, wave defense, and hydraulic profile.

The evaluation of seismic foundation stability was based on a review and analysis of the offshore borings and the seafloor cone penetration tests. Based on this study, the following minimum excavation depths were established to preclude foundation failure resulting from earthquake-induced liquefaction: east of the San Andreas fault, 10 feet; west of the San Andreas fault, 20 feet.

From 11,000 feet offshore and westward, portions of the trench may be excavated into medium stiff to stiff, moderately overconsolidated clays. While some excess porewater pressure development was anticipated during the design earthquake, the clays were not considered susceptible to liquefaction. Because the seafloor in this area is nearly flat (slope of 0.2 percent or less), the potential for landsliding or lateral spreading is considered to be negligible.

Trench excavation depths were dictated by hydraulic profiles and/or wave defense considerations; these resulted in excavation depths deeper than required for seismic foundation stability along the entire alignment. The wave defense philosophy involved the burial of the conduit and protective riprap below the seafloor.

It is anticipated that the natural fine sands used to restore the seafloor grade will infiltrate downwards under gravity and wave-induced water pressure fluctuations, and eventually fill the voids between the riprap. The sand infilling would impede the dissipation of wave-induced or earthquake-induced excess porewater pressures in the backfill surrounding the pipe, as discussed below.

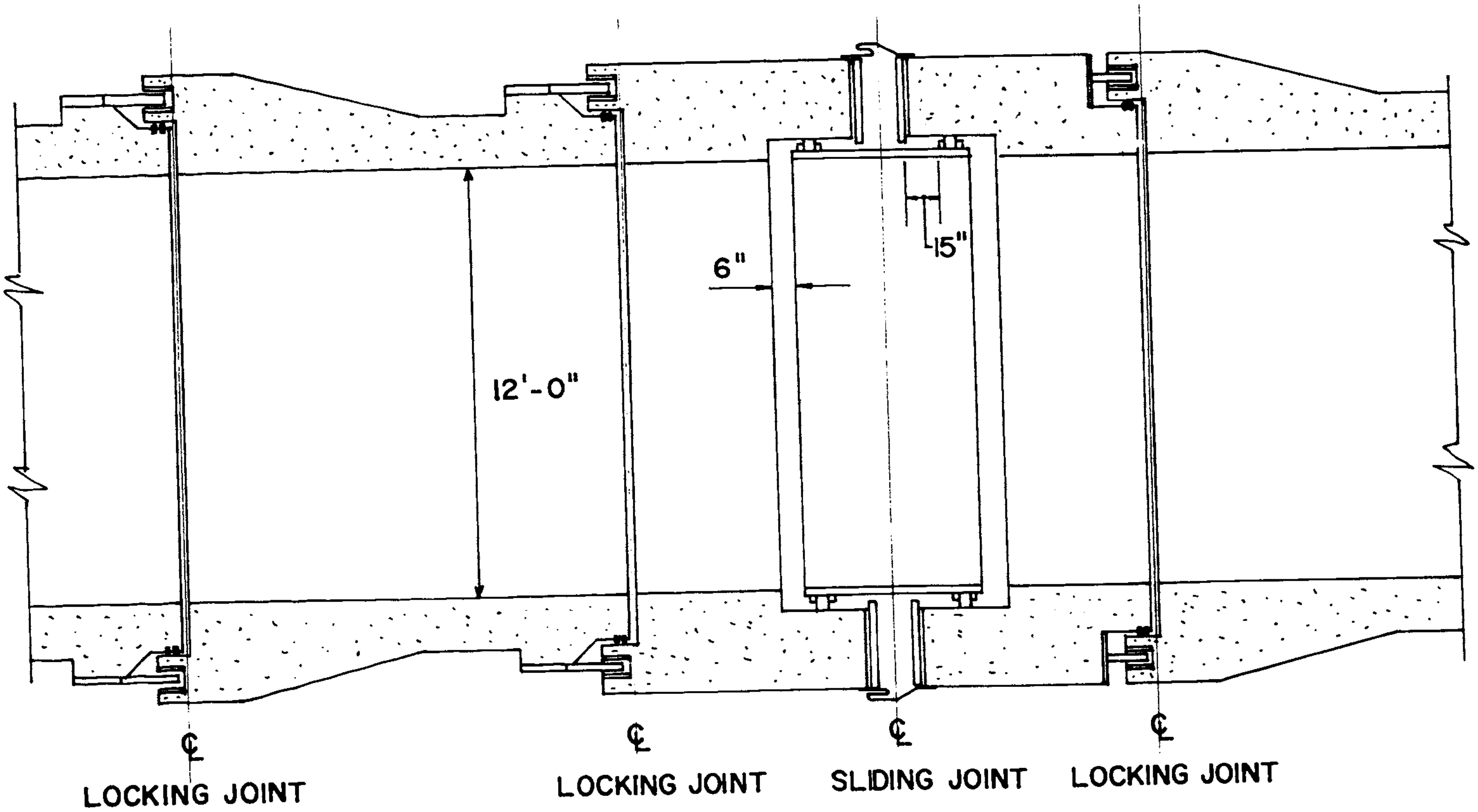

Figure 4 LONGITUDINAL SECTION OF SPECIAL JOINTS

Backfill Gradation and Geometry

Early in the design process, it was recognized that backfill placed in the ocean environment would be relatively loose, and would be susceptible to both wave-induced and earthquake-induced liquefaction. It was also concluded that a design solution that would mitigate against earthquake-induced liquefaction effects would equally mitigate against wave-induced liquefaction effects.

It was felt that if the backfill was highly pervious, porewater pressure redistribution during the period of earthquake-induced shaking would prevent the development of the full gradient of excess porewater pressure and the resulting lifting forces on buried pipe sections. The increase in excess porewater pressure versus time for an idealized one-dimensional backfill configuration was analyzed using the computer program APOLLO (Seed and Martin, 1978). It was assumed that the overlying natural sand backfill would be essentially impervious compared to the backfill surrounding the pipe. The presence of riprap was neglected, and the pipe itself was not modelled. It was further assumed that, in the absence of porewater pressure redistribution, backfill liquefaction would occur simultaneously throughout the depth, after 15 seconds of strong ground shaking.

The results of the analyses for two backfill permeabilities are shown in Figures 5a and 5b. For a sand backfill with a permeability $k = 10^{-3}$ cm/sec, there is little redistribution and full buoyancy conditions are approached after about 16 seconds (Figure 5a). For a gravel backfill with $k = 1$ cm/sec there is significant redistribution (Figure 5b), with the excess porewater pressure essentially constant with depth. A pipe enclosed in the gravel backfill would be subject to an equal all-around pressure increase, with no net uplift force.

The results of the numerical analyses and considerations of constructibility led to the selection of the Type I gravel backfill around the pipe as shown on Figure 6. The Type II backfill is a graded filter course to minimize infiltration of the natural sands into the Type I backfill. The armor stone layers (Type III and Type IV) are for wave defense should the native sand backfill be removed during a major storm. The excavation slope shown is based on the results of the test pit program. Excavation and backfill slopes shown are for the purpose of computing contract pay quantities and are not predictions of actual constructed slopes.

CLOSURE

The plans and specifications for San Francisco's Southwest Ocean Outfall are the result of an integrated process of exploration, analysis, consultation, and design with inputs received from specialists in a variety of scientific and engineering disciplines. This process is vital on major projects and seems particularly important in light of the potentially hostile seismic and ocean conditions prevalent in the Outfall project area. The information presented in this paper is intended to be of use to the designers of future offshore conduits across major geologic discontinuities.

ACKNOWLEDGEMENTS

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Principal subconsultant for hydraulic and sanitary design is CH2M-Hill, Inc. Cost estimates and special studies on constructibility are provided by H. V. Anderson of H. V. Anderson Engineers, San Rafael, California.

Counsel and guidance concerning seismic design and constructibility of the Outfall system are provided by the Seismic Advisory Board. This distinguished panel of consultants, under the chairmanship of T. R. Kuesel of Parson Brinckerhoff, includes H. B. Seed, B. C. Gerwick, Jr., B. A. Bolt, and J. W. Johnson of the University of California, Berkeley, G. W. Housner and N. H. Brooks of the California Institute of Technology, and N. M. Newmark.

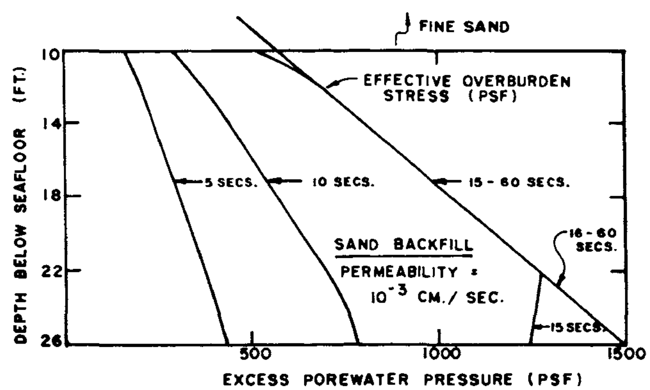

Figure 5a EXCESS POREWATER PRESSURE GENERATION IN SAND BACKFILL

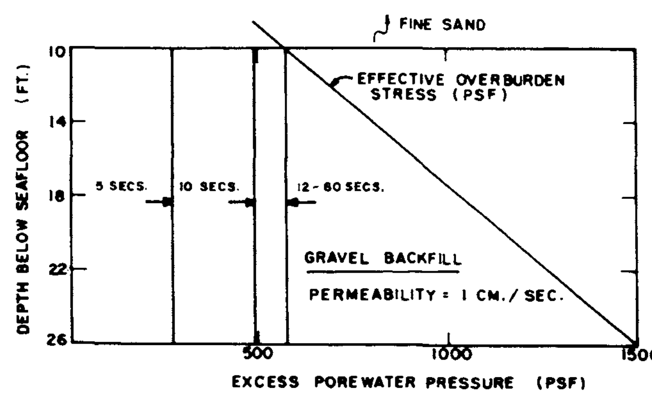

Figure 5b EXCESS POREWATER PRESSURE GENERATION IN GRAVEL BACKFILL

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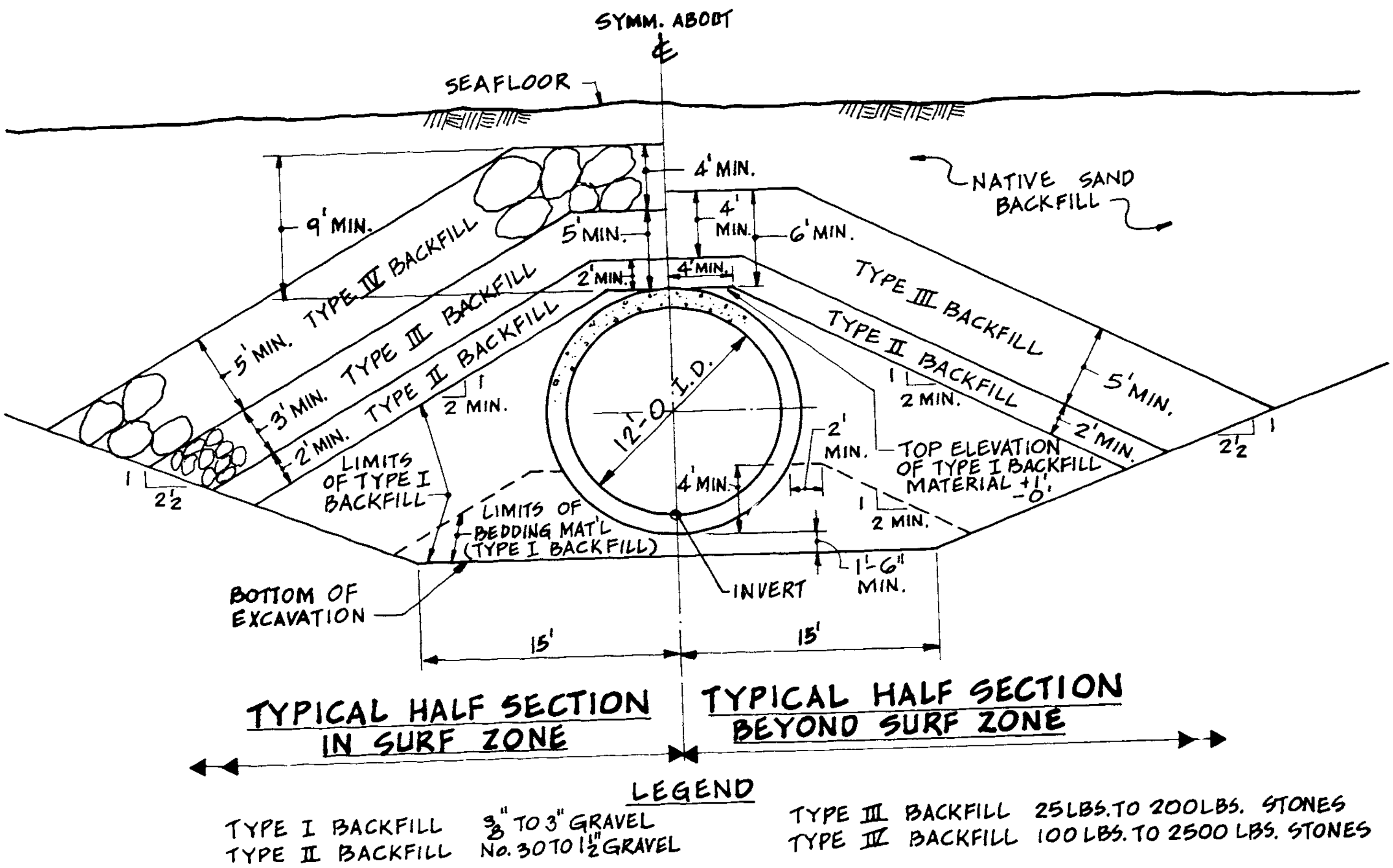

Figure 6 TYPICAL BACKFILL SECTIONS